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[redacted]

31 July 1964
HH:bb:362
(997-112)

MEMORANDUM

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STATINTL To: [redacted]
From: [redacted]

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Subject: Variation of Density with Numerical Aperture
CC: [redacted]

INTRODUCTION

This memorandum presents the results of a study to determine the dependence of photographic density of various films on parameters such as numerical aperture, film gamma, development time, granularity and exposure. Explicitely the objective was to provide the rules for predicting density for a particular numerical aperture when the density was known for a different numerical aperture. The prime reason for density difference with numerical aperture is the scattering of light by the grainy emulsion.

This memo contains three sections. The first describes the experimental procedure for measuring density values of various samples, the second presents the results in terms of Callier's q factor, and the third contains recommendations for a procedure for density value prediction.

EXPERIMENTAL PROCEDURE

The general procedure for obtaining density values is to scan a step wedge (on the sample film) with a microdensitometer using several combinations of numerical apertures of the source and detector. The numerical aperture of the source is the sine of the half-angle of the cone of light illuminating each point of the sample, and the numerical aperture of the detector is the sine of the half-angle of the cone of light collected from each point on the sample by the detector. STATINTL The sample films included in the scanning were chosen on the basis of availability. [redacted] These films provide a large range in granularity which is a parameter strongly related to scattering. The samples were produced

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STATINTL by imaging a [redacted] step wedge onto the samples with an enlarger. A reduction in image size was provided such that all densities in the wedge could be measured from a single scan by the [redacted] Model 4 microdensitometer. In addition to the size reduction, the image was slightly defocused to assure that density fluctuation in the steps of the [redacted] wedge were not reproduced on the sample. The amount of defocus was assumed sufficient when edge blurring was in evidence to the eye since the fluctuations were not visible even when in focus. The defocus was not enough to smear the steps together however. The processing of the sample films conformed to normal practice.* Table (1) lists the samples generated along with their nominal granularity values and processing. In one case [redacted] the processing was varied by including development time, both long and short compared to the normal 5 minutes. These are marked by * in Table (1).

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Film Type	σ_D	Developer	Development Time
[redacted]	0.085	D-19	8 min.
	0.020	DK-50	5
	0.014	D-19	5
	<0.01	DK-50	4
	---	D-19	2*
	0.055	D-19	5
	---	D-19	12 *
		D-19	5

TABLE (1)

FILMS TESTED

The imaged step wedge on each of the sample films was scanned and the densities recorded for several combinations of source and detector numerical apertures. The numerical aperture combinations used are given in Table (2). In each case a large scanning aperture area (greater than 2000 μ^2) was provided to keep fluctuation due to granularity at a minimum thus minimizing the error in the measured density value.

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* [redacted] Aerial Handbook

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Source N.A.	Detector N.A.
0.1	0.1
0.1	0.25
0.1	0.4
0.25	0.25
0.25	0.4
0.4	0.4

TABLE (2)

NUMERICAL APERTURE COMBINATIONS
FOR SCANNING

RESULTS

In order to avoid confusion in terms, the density of a particular sample will be given arguments that describe how it was measured. For the remainder of this memo the following notation will be adopted when necessary

$$D = D(x, y) \qquad (1)$$

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where x and y are the numerical apertures of the source and detector respectively.

As an illustration of how density varies with numerical aperture, Figure (1) includes plots for [redacted] For each of the two films three levels were selected from the step wedge images. The normally decreasing density with increasing numerical aperture is in evidence for [redacted] which has a moderately high granularity. On the other hand, a slight rise in density for increasing numerical aperture is a possibility for [redacted] In the case of Figure (1c) where both numerical apertures increase together, an increase in density could be attributed simply to the longer path lengths through the three-dimensional emulsion. An upper bound for this density rise has been derived for a non-scattering emulsion,* and the bounds properly lie above the curves of Figure (1c). However, the curves of Figure (1d) have the same rise characteristics as Figure (1c), but there is no known theoretical non-scattering basis for a rise in density with increasing detector numerical aperture. Therefore, the slight rises of Figure (1c) and (1d) are attributed to errors in density measurement.

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* [redacted] Memorandum, HH:bb:291-pa (997-112), Revised 9 July 1964.

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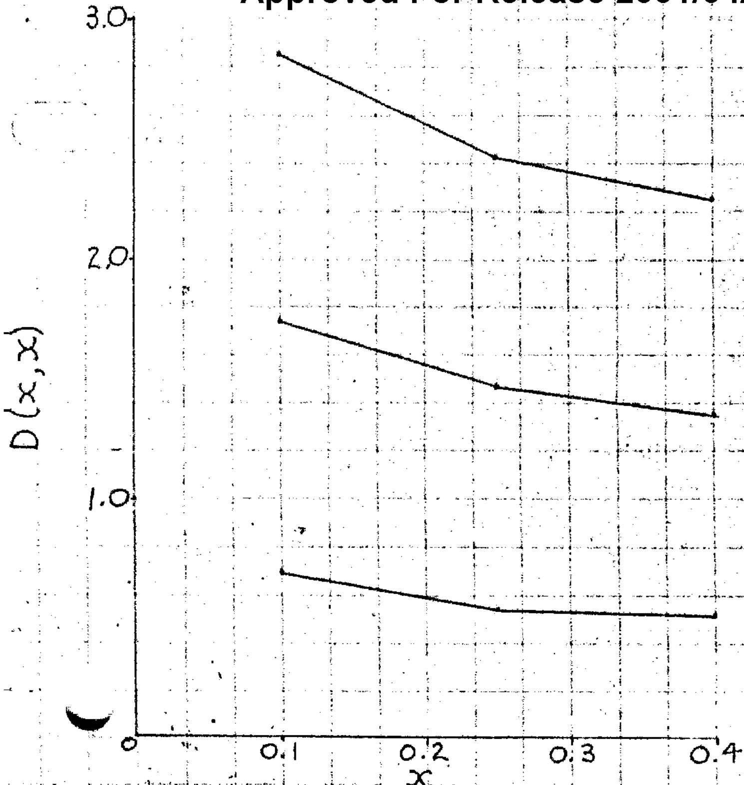
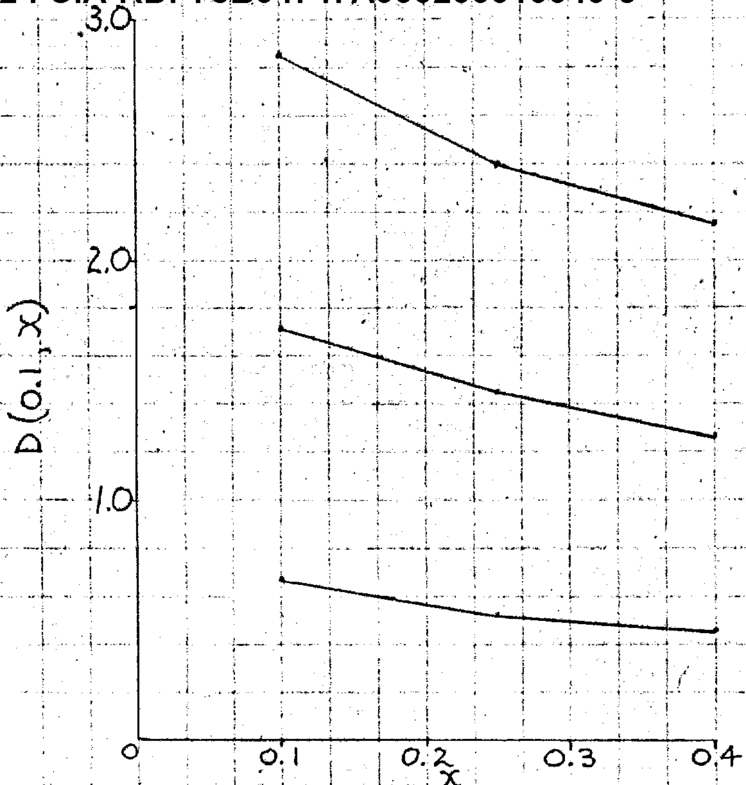
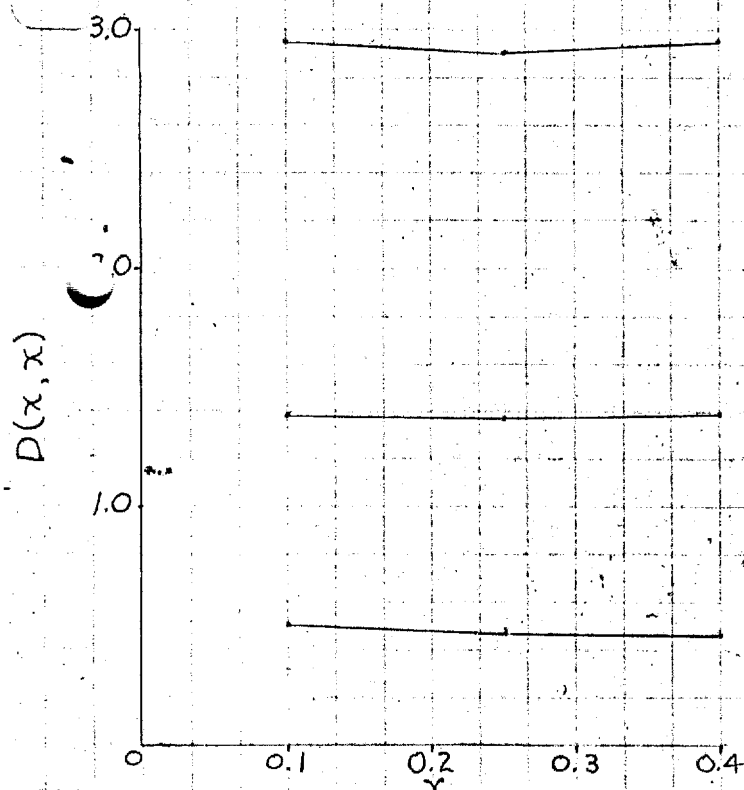


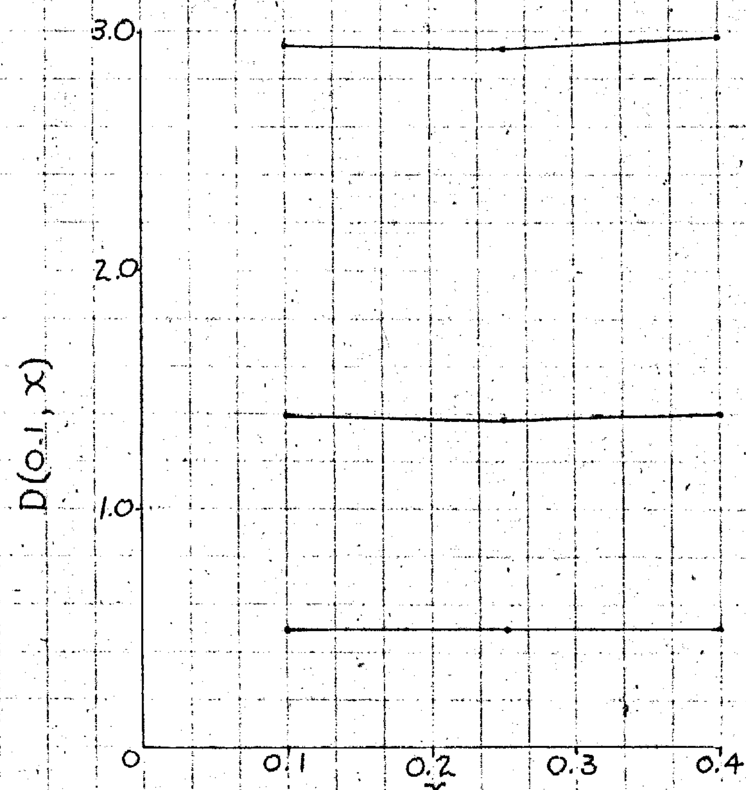
(a) [redacted]



(b) STATINTL



(c) [redacted]



(d) STATINTL

Fig. (1) Illustrations of Density Variations with Numerical Aperture

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The usual practice in describing the variation of density with numerical aperture is with "Callier's Q factor" defined by:

$$Q = \frac{D(0,0)}{D(0,1)} \tag{2}$$

Although numerical apertures of zero are unattainable in practice, they are used to indicate "smallness". Since specular density [$D(0,0)$] is very sensitive to the actual values of the numerical apertures used, the factor Q is only of value when the numerical apertures are known accurately. A more generalized factor (q) can be defined:

$$q \equiv \frac{D(x,y)}{D(0,1)} \tag{3}$$

Since the only data obtained for this memorandum was for the numerical apertures of Table (2), the following factor (q') is used for the remainder of this memo.*

$$q' \equiv \frac{D(x,y)}{D(0.1,0.4)} \tag{4}$$

The usefulness of these factors is in the prediction of a density $D(x_2, y_2)$ when $D(x_1, y_1)$ is known. Thus:

$$D(x_2, y_2) = \left[\frac{q'(x_2, y_2)}{q'(x_1, y_1)}\right] D(x_1, y_1) \tag{5}$$

Figures (2) through (8) show how $q'(x,y)$ varies with $D(x,y)$ for all the film types in Table (1) with the exception of [redacted] whose q' factor is unity within the measurement error. For each film type several combinations of numerical apertures (x, y) from Table (2) are included, and it is seen that for increasing density, q' decreases. Some of the aperture combinations in Table (2) are not plotted since they are close to unity for all densities. At small values of D however the value of q approaches unity since in the limit there are no developed grains in the emulsion and hence negligible scattering. It is also seen that for a particular combination of numerical apertures, high values of granularity (σ from Table (1)) lead to high values of q'.

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For one film type [redacted] the processing time was varied from 2 minutes to 12 minutes in order to find the effect on q'. Comparison of Figures (5), (6) and (7) shows little change in q', but although the density of a particular step increased with increasing development time, the film γ did not change significantly.

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* The diffuse densities [$D(0,1)$] were not obtained due to trouble with the [redacted] densitometer. See [redacted] Memorandum by [redacted] EH:bb:359, (997-112) 7 August 1964.

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Fig. (2) - Variation of q' with D for Film Type [redacted]

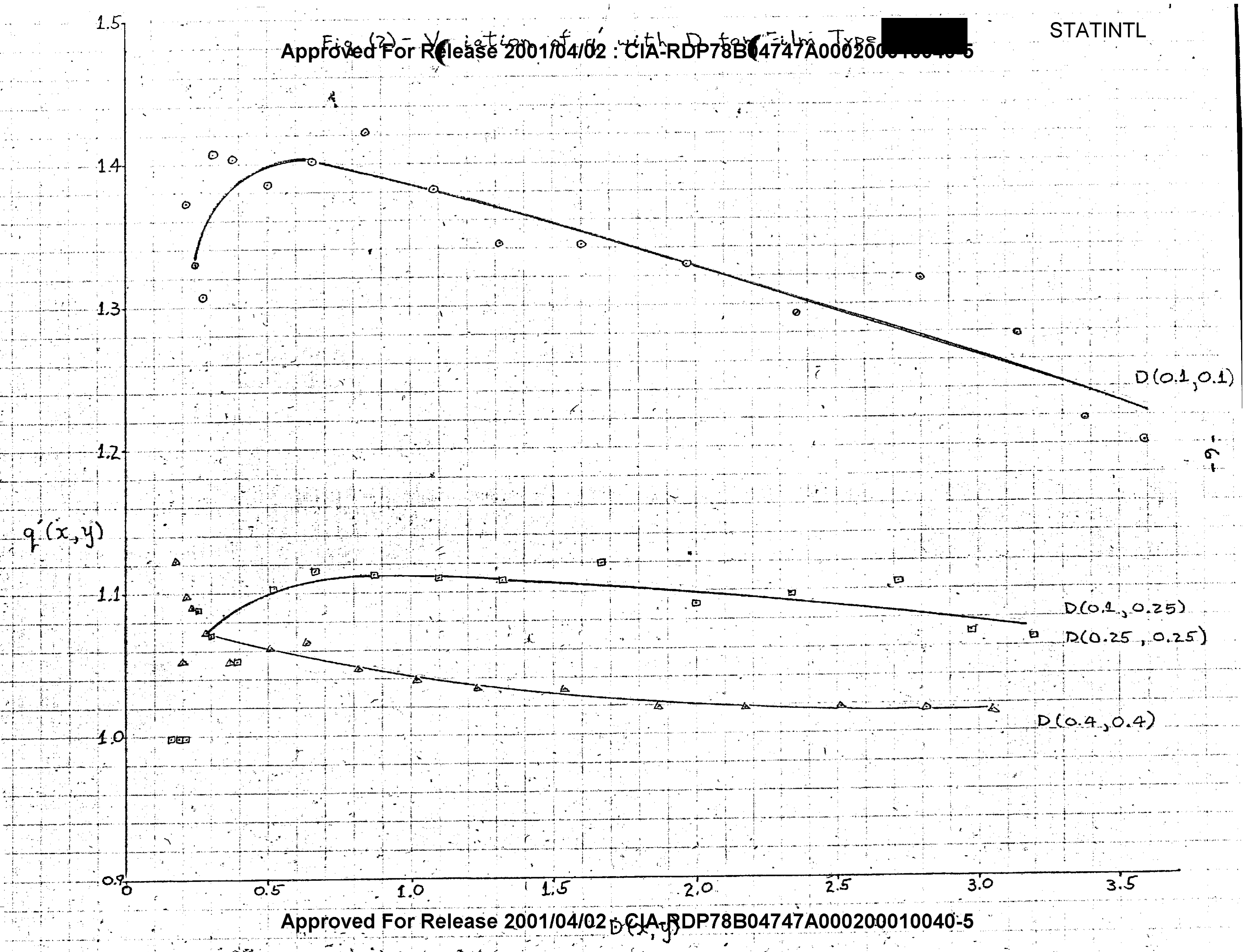

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Fig. (3) – Variation of q' with D for Film Type [redacted]

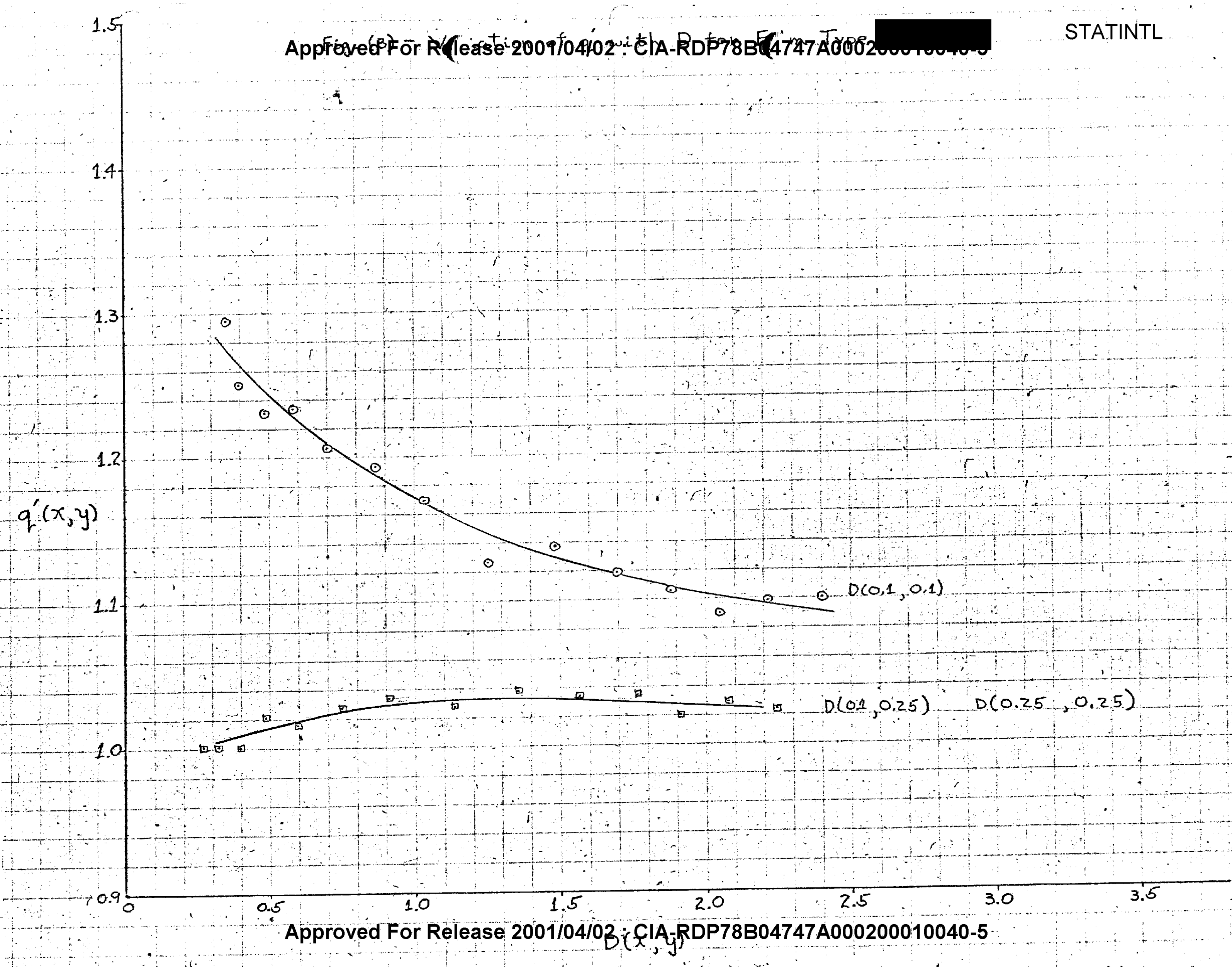

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Fig. (4) - Variation of q' with D for Film Type [redacted]

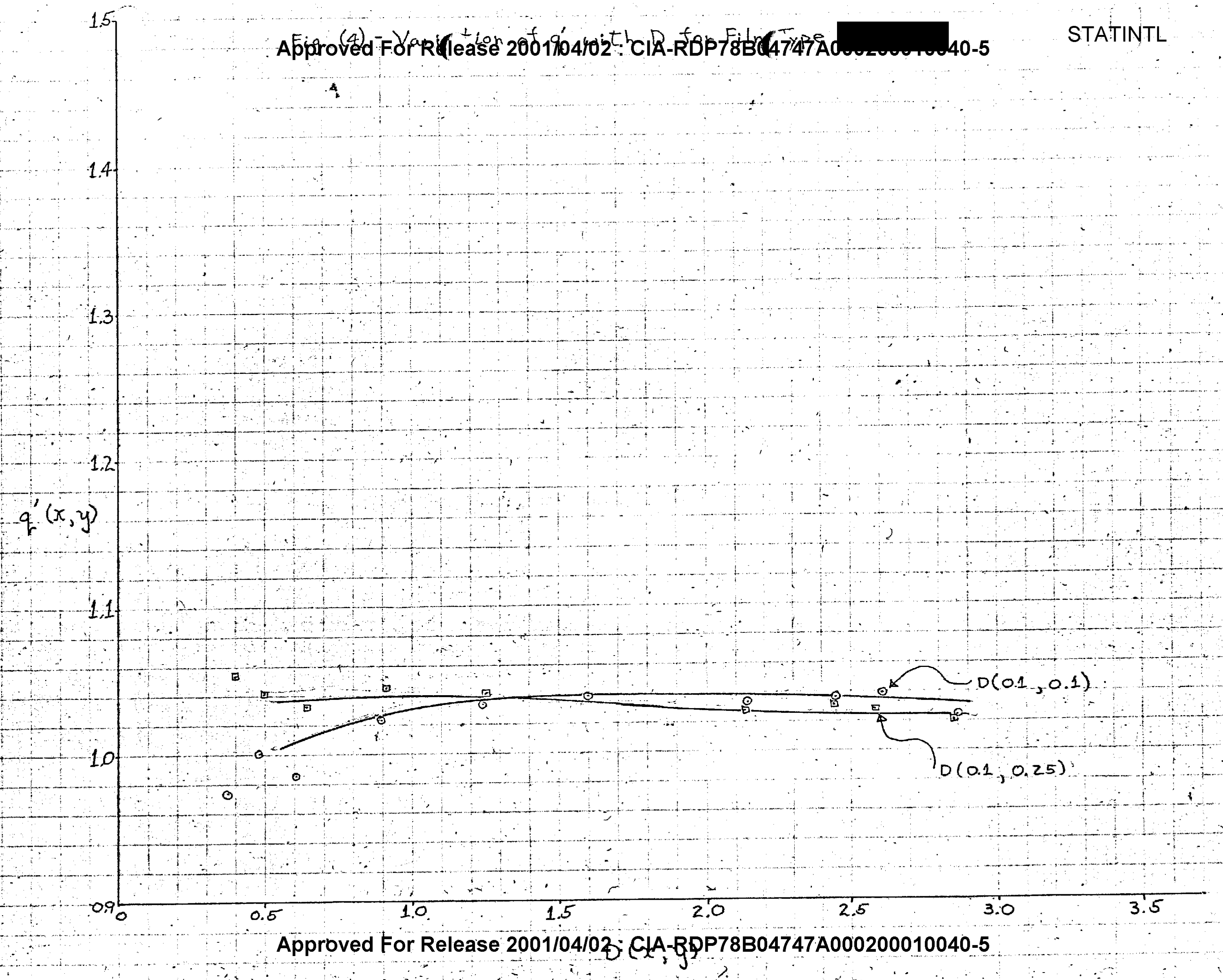

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Fig. (5) - Variation of q′ with D for Film [redacted] (2 Min. Development)

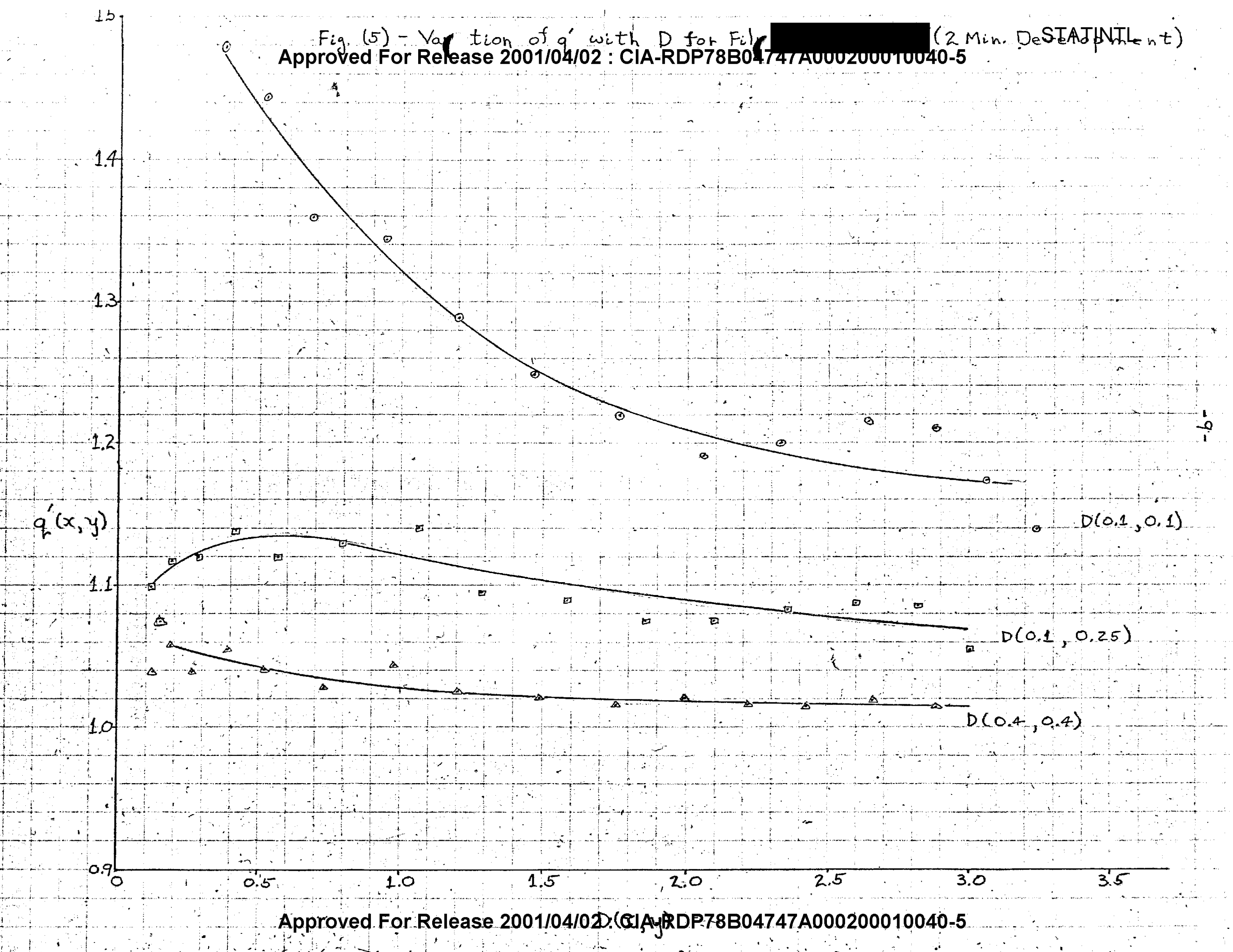

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Fig. (6) - Variation of q' with D for Film [redacted] (5 Min. Development)

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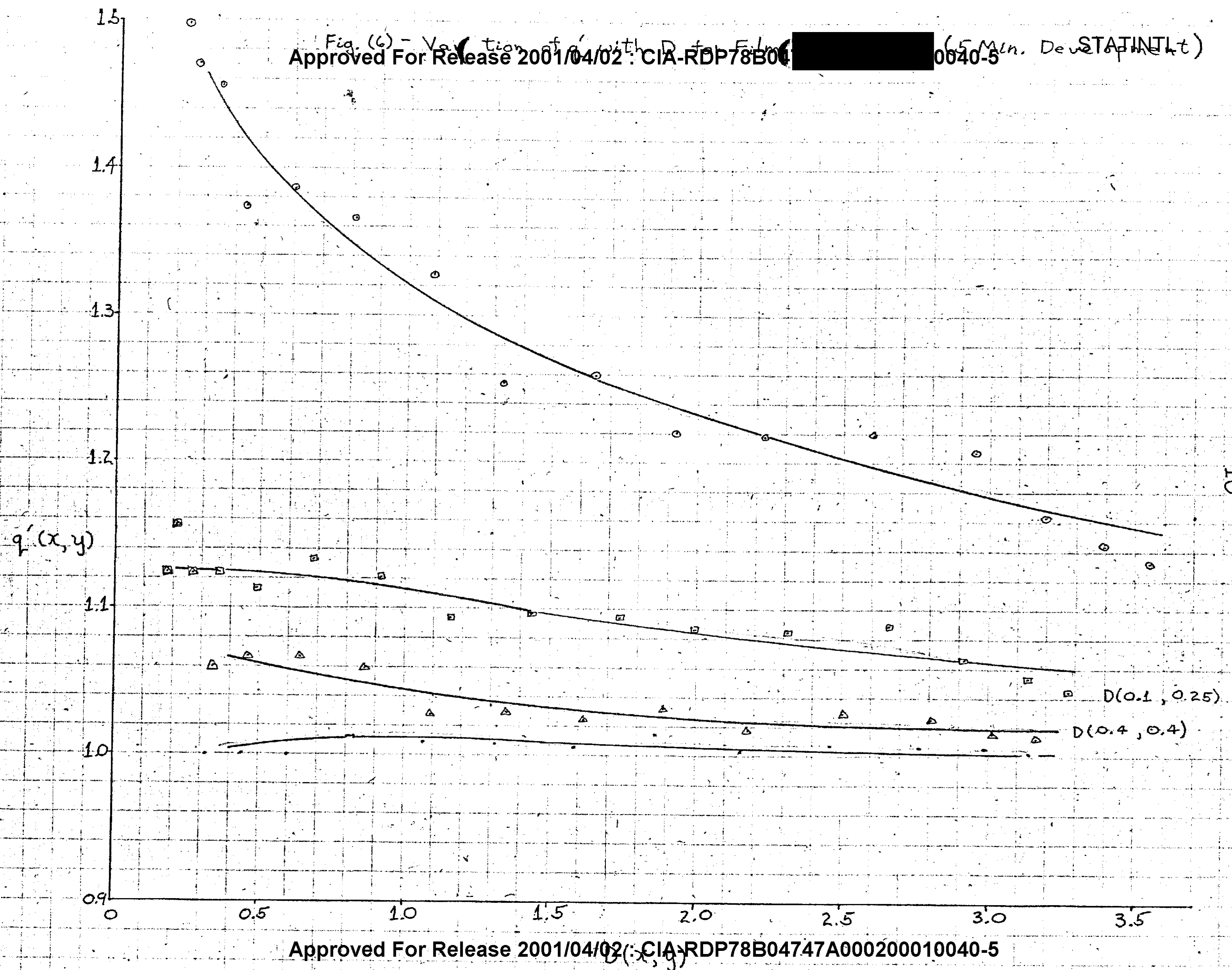

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Fig. (7) - Variation of q′ with D for Film Type [redacted] (12 Min. Development)

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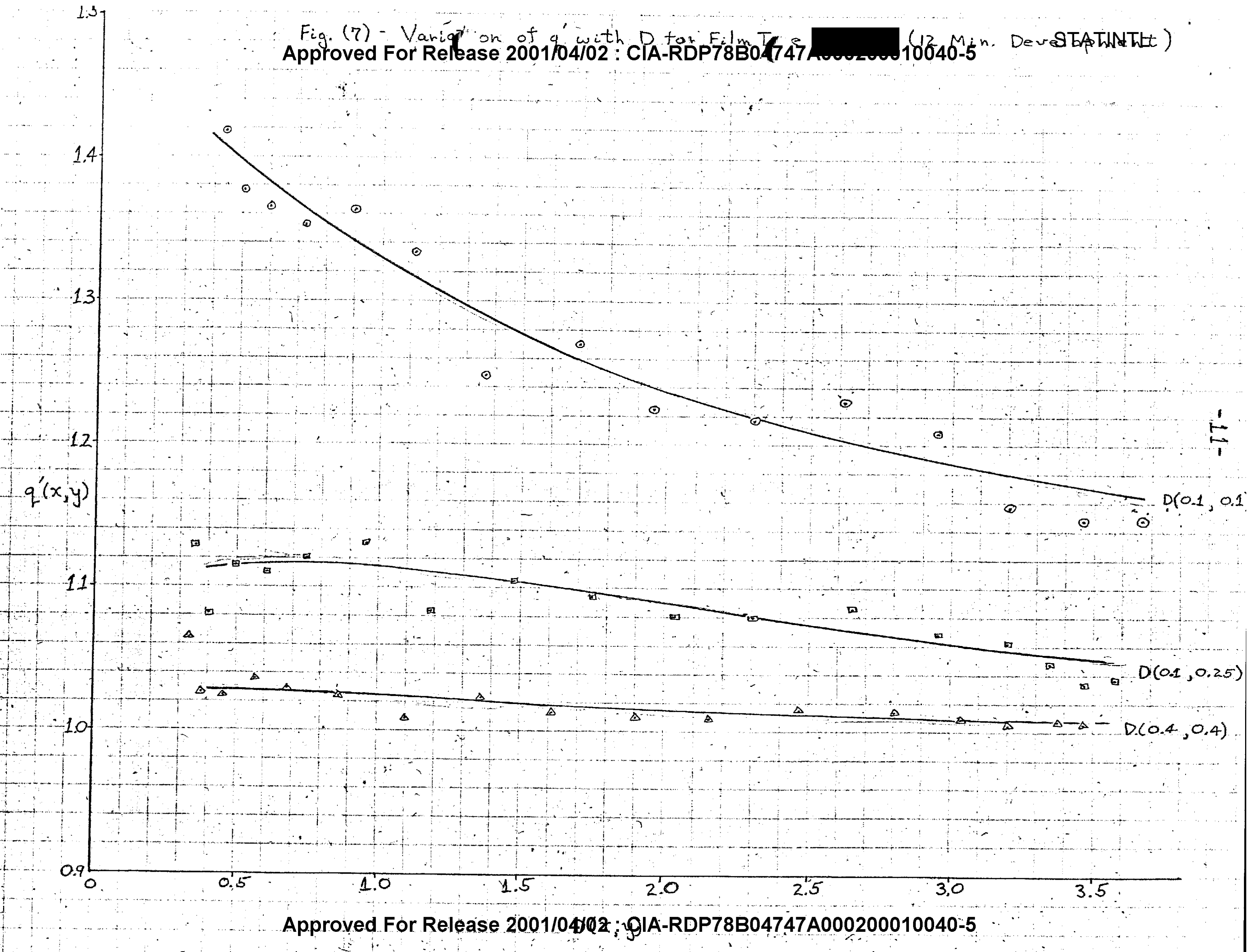

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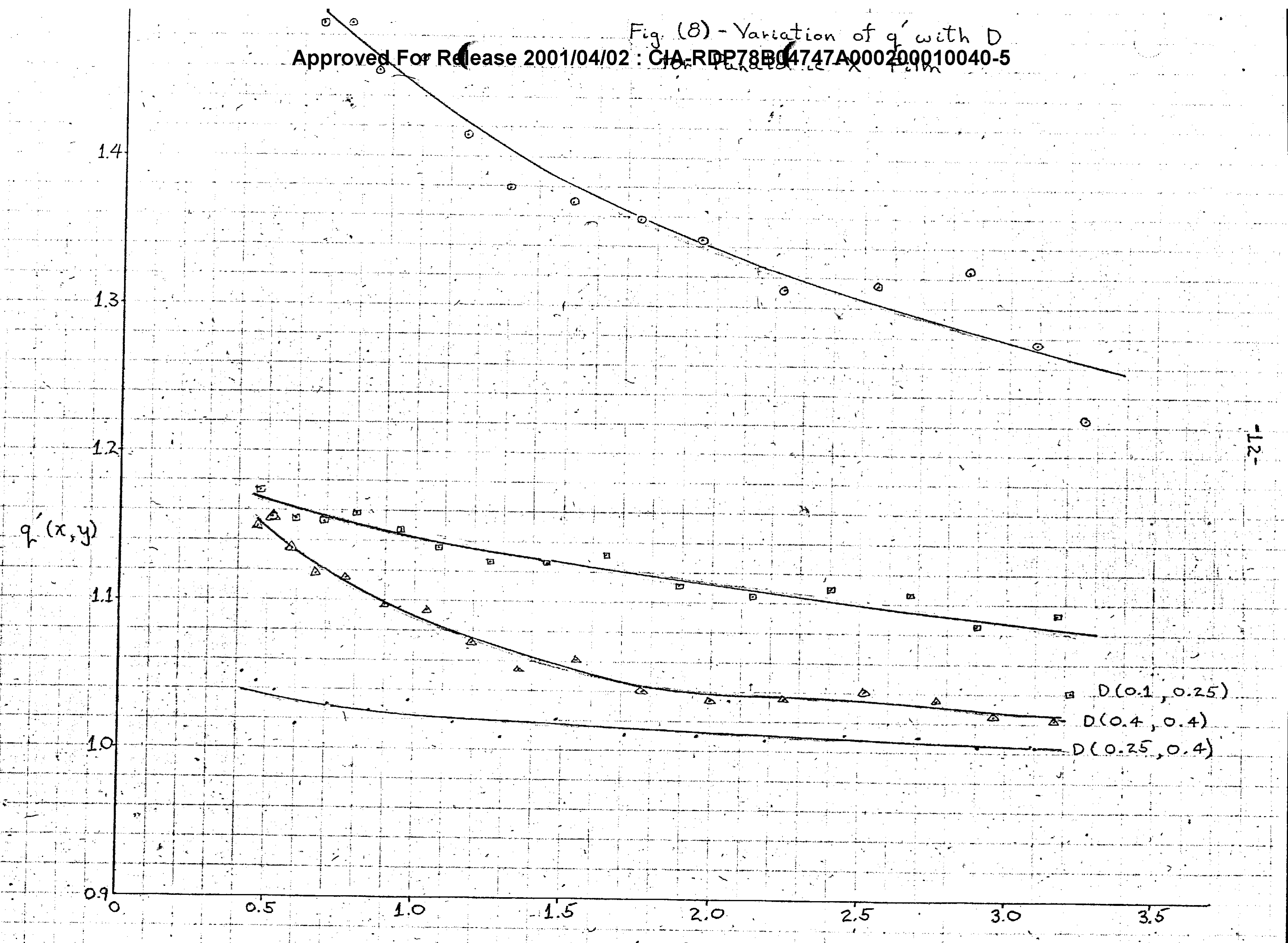
Fig. (8) - Variation of q′ with D



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This is an effect of the developer (D-19) since other developers (such as D-76) yield a change in γ with increasing development time. The variation of Q with γ has been investigated and a typical trend is shown in Figure (9).*

STATINTL It has been shown by [redacted]* that Q can be expressed as a logarithmic function of density; explicitly that a plot of log Q vs. log D yields straight lines. Figures (10) and (11) are plots of log $q(x, y)$ vs. log $D(x,y)$ and the straight line relation was found. The oscillations about the line are probably due to certain non-linearities present in the microdensitometer electronics.

RECOMMENDATIONS

. It is recommended that each film type be sampled at several different densities for the numerical aperture combinations of interest and plots made of $q(x,y)$ vs. $D(x,y)$, and $q(x,y)$ vs. $D(0,1)$ for inclusion in the microdensitometer handbook. These plots would be the working graphs from which $D(x_2, y_2)$ can be found when $D(x_1, y_1)$ is known. This is done as illustrated in Figure (12) by first finding $D(0,1)$ by determining $q(x_1, y_1)$ from graph (a) and dividing this value into $D(x_1, y_1)$.

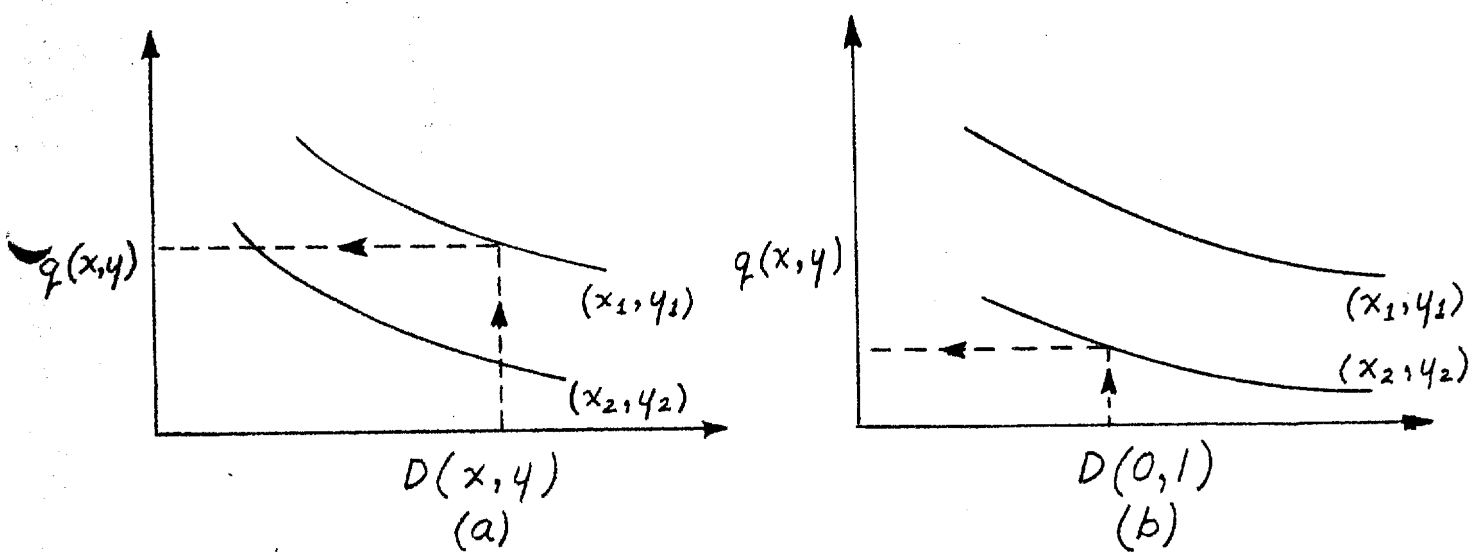

FIGURE (12)

WORKING GRAPHS FOR DENSITY PREDICTION

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* [redacted] Fundamentals of Photographic Theory (1960) Chapter 10

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Fig. (9) - Typical Variation of Q with Film Gamma

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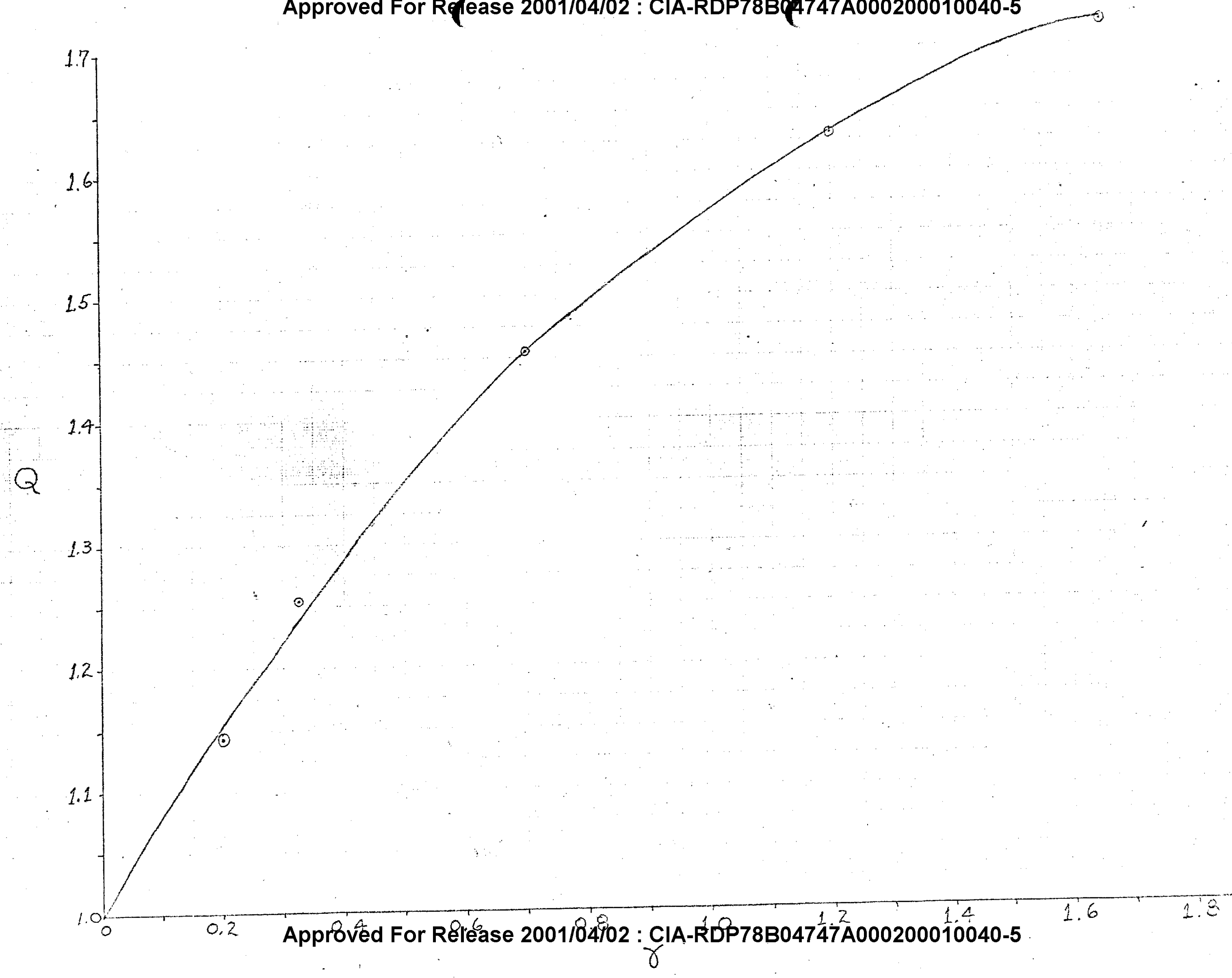

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for [redacted] (2 Min. Development)

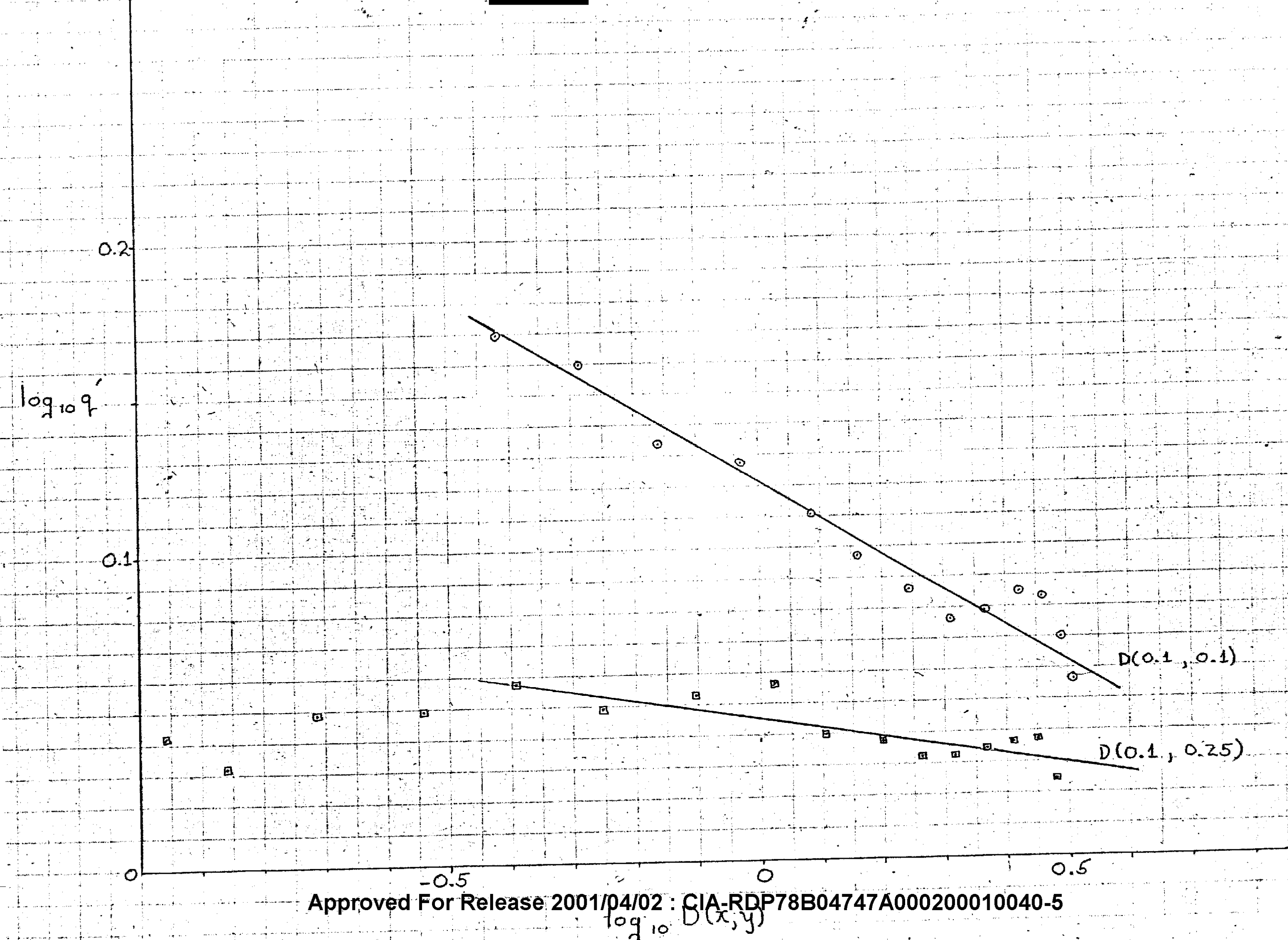

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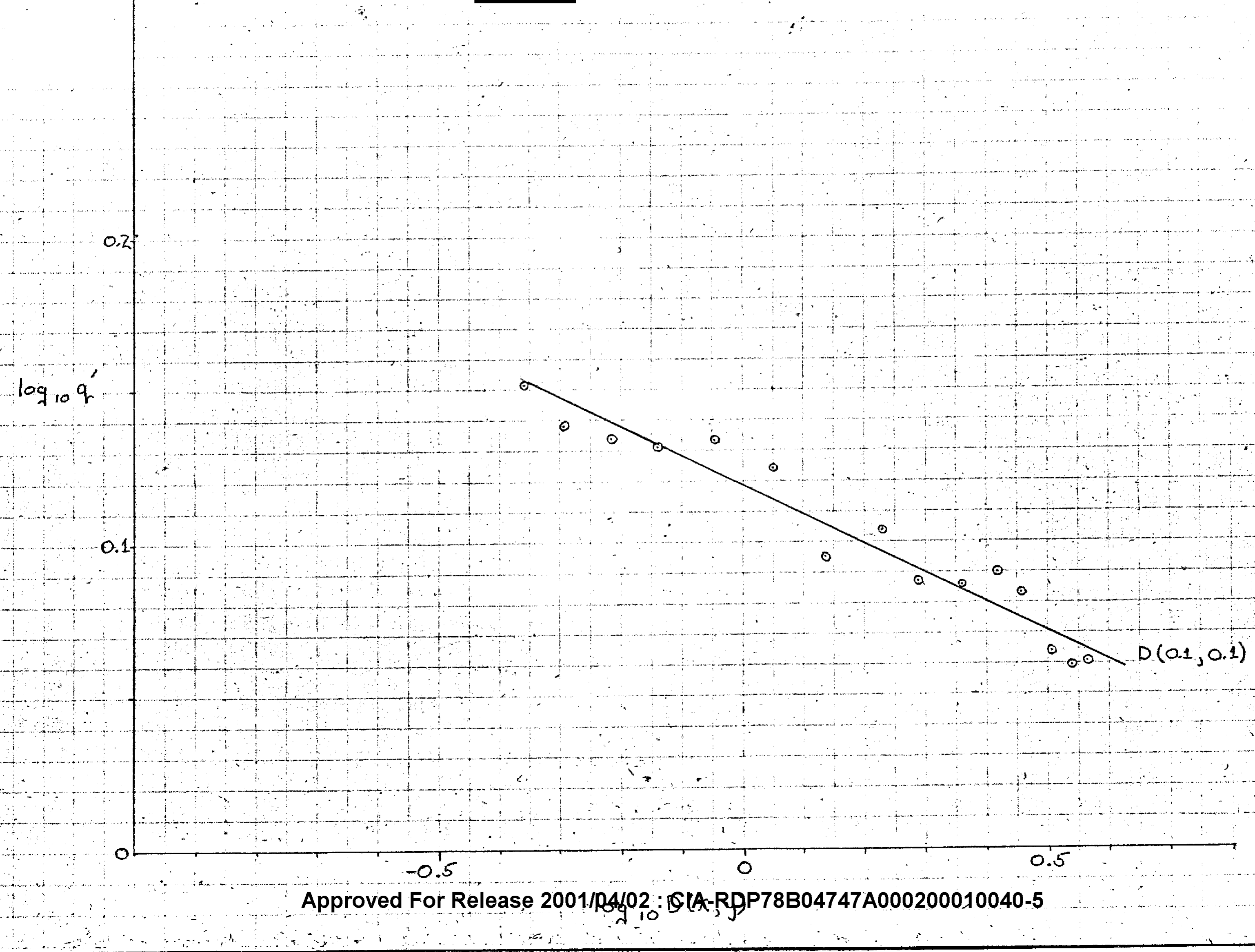
Fig. (11) Linear Relation between log q' and log D for [redacted] (12 Min. Development)



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The second step is to find $D(x_2, y_2)$ by determining $q(x_2, y_2)$ from graph (b) and then multiply this value by the value of $D(0,1)$.

In order to provide the graphs discussed above, it is first necessary to measure the corresponding diffuse densities. If the trouble presently encountered with the [redacted] densitometer cannot be overcome, it is then recommended that $D(0.1, 0.4)$ be substituted in place of $D(0,1)$ and of course $q'(x,y)$ in place of $q(x,y)$.

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[redacted]

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